British Journal of Industrial Medicine 1987;44:149–160

Further assessment of the effects of occupational radiation exposure in the United Kingdom Atomic Energy Authority mortality study

HAZEL INSKIP, VALERIE BERAL, PATRICIA FRASER, MARGARET BOOTH, D COLEMAN, ANN BROWN

From the Epidemiological Monitoring Unit, Department of Epidemiology, London School of Hygiene and Tropical Medicine, London WC1E 7HT, UK

ABSTRACT The United Kingdom Atomic Energy Authority mortality study was designed to investigate the relation between exposure to ionising radiation and mortality among the authority's employees. The present paper describes some of the problems encountered in assessing occupational exposure to low dose radiation and examines whether the study's conclusions about the relation between exposure and mortality could be affected by the methods used. The study covered the years 1946 to 1979 during which time the frequency with which personal film dosimeters were issued changed from weekly to monthly, and the threshold level below which measurements were not made decreased 20-fold. Exposure from "below threshold" readings made an important contribution to total exposure in the early years. Estimates, based on the remeasurement of a sample of old films, indicated that the average whole body exposure before 1961 may have been about double that which was measured. Furthermore, although records were kept of when dosimeters were lost or damaged, the associated exposures were unknown and could only be estimated. Workers whose dosimeter readings were missing for more than 5% of the time during which they were monitored had higher all cause mortality ($p = 0·04$) and higher mortality from accidents and violence ($p = 0·05$) than other radiation workers. The results of analyses of mortality in relation to whole body exposure were compared when (*a*) the exposures included estimates of the below threshold and missing exposures and (*b*) when these exposures were assumed to be zero. Some of the findings differed, but none changed sufficiently to alter the general conclusions. Although the trend in mortality from all cancers changed from one in which the increase with exposure was far from statistically significant ($p = 0·3$) when the below threshold and missing values were assumed to be zero to one that approached significance ($p = 0·06$) after they were estimated, calculations of the annual excess deaths from cancer per unit dose resulted in broadly similar estimates. Studies of workers exposed to ionising radiation usually focus on mortality in relation to whole body exposure. In the present paper its relation to neutron and surface exposure is also examined. Workers with measured neutron exposures had significantly lower all cause mortality than other workers with a radiation record ($p = 0·03$). Surface exposure was significantly related to mortality from all cancers ($p = 0·02$) and prostatic cancer ($p < 0·001$). Some data on cancer registration are presented but these cannot be readily interpreted because cancer registration details were available only for ex-employees who may not be typical of the workforce as a whole.

The United Kingdom Atomic Energy Authority (UKAEA) mortality study was designed to investigate the relation between exposure to ionising radiation and mortality among the authority's employees. The methods of data collection and validation, and some of the main findings have been described elsewhere.[1 2] Overall, the mortality rates among the authority's employees were below the national average, with no major differences in mortality between those who were monitored for exposure to radiation and those who were not. The

Accepted 27 August 1986

only cause of death found to be significantly associated with certain types of exposure to radiation was prostatic cancer.

Studies of workers exposed to radiation commonly consider exposure to whole body radiation, which includes contributions from X and γ radiation and sometimes from neutrons. These types of radiation penetrate the body and irradiate tissues beneath the surface. The measurements of such radiation are generally made from dosimeters worn outside the body and, although the relation is not straightforward, they are taken to be indicative of the absorbed dose in the tissues. Workers may, however, be exposed to forms and sources of radiation other than those which contribute to whole body exposure. Beta particles and low energy photons that emanate from sources outside the body irradiate only the superficial layers of the skin and contribute to the "surface exposure" that is measured by dosimeters worn externally and is recorded separately from the whole body dose. Radionuclides may be ingested or inhaled and, although workers are monitored for possible contamination by such substances, the associated tissue doses are often difficult to estimate and are generally not included in the whole body measurements.[3]

Previous analyses focused on whole body exposure, although some analyses were presented on individuals monitored for possible contamination by certain radionuclides.[2] In those analyses the whole body exposures which were below the threshold level of the measuring devices in use at the time were taken to be zero, as were the exposures associated with dosimeters that were lost or damaged. In the present paper mortality is examined in relation to a revised estimate of each individual's exposure which has been obtained by estimating the contributions from below theshold readings and for lost or damaged dosimeters. The relation between mortality and surface and neutron exposures are also described.

A total of 3433 deaths among 39 547 employees are analysed. These data relate the same authority establishments and period of follow up already described.[2] They contain additional deaths notified too late to be included previously and some identified during validation checks.[1 2] The causes of death were coded according to the 8th revision of the International Classification of Diseases.[4] Cancer registration data, collected for the authority's ex-employees but not presented before, are also discussed.

Analyses in relation to radiation exposure

THE DATA

Workers exposed to ionising radiation are unusual among occupational groups in that personal monitoring of exposure is obligatory, as is the maintenance of monitoring records by the employer. The following information was extracted from each employee's annual radiation record:

(1) Total whole body exposure—an estimate of the exposure which penetrates the body, the main contributions being from X and γ rays and sometimes neutrons;

(2) Total surface exposure—an estimate of exposure received at the surface of the body, comprising the whole body exposure plus that received from β particles and low energy photons;

(3) Total exposure from neutrons;

(4) Number of dosimeters issued;

(5) Number of dosimeter readings that were below threshold—that is, where the exposure received, if any, was below the level that could be detected by the dosimeter reading equipment in use at the time;

(6) Number of weeks for which dosimeters were issued but a measurement of the exposure was missing—usually because the dosimeters had been lost or damaged. Under these circumstances, for radiation protection purposes, the UKAEA generally record a "notional dose," this being the maximum permissible dose during the period when measurements were missing. Total annual notional doses were also recorded.

ANALYTICAL METHODS AND SELECTION OF EXPOSURE CATEGORIES

Various statistical methods have been used for analysing mortality in relation to occupational radiation exposure, many of them being applications of Cox's proportional hazards model.[5] Gilbert and Kneale *et al* compared the cumulative exposures of those dying from the cause of interest with the cumulative exposures of all other individuals who were similar in respect of sex, age, and other confounding factors.[6 7] Gilbert and Marks[8] and Darby and Reissland[9] grouped individuals into categories of exposure, and then tested for trends in mortality with increasing dose. These methods have similar power,[10] but when the distribution of the cumulative exposures is highly skewed, as is the case for the UKAEA's workforce (fig 1), dividing the exposure into categories is preferred since it has the advantage of not giving undue weight to the few individuals with particularly high levels of exposure. The analysis used here uses grouping of exposures and is similar to the methods described by Gilbert and Marks[8] and Darby and Reissland.[9] Person-years at risk are calculated, stratified by age, sex, social class, calendar period, and authority establishment. Within each stratum the proportion of the person-years falling into each exposure group is obtained. These proportions are multiplied by the total observed deaths in the stratum to derive the expected deaths. The sum of these across

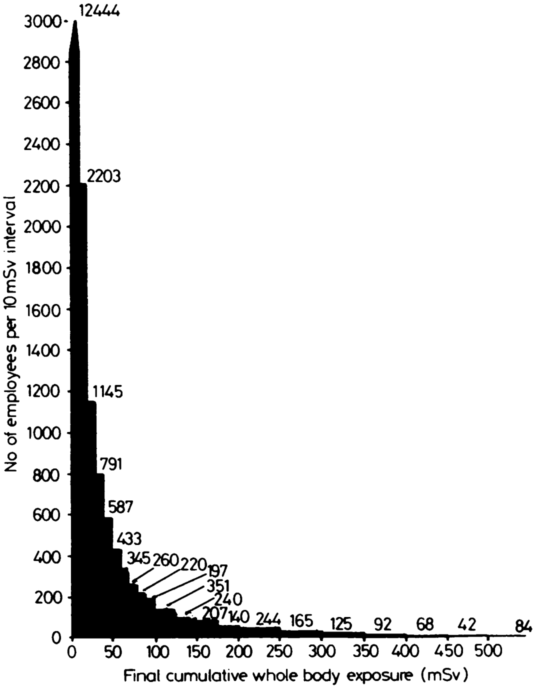

Fig 1 *Distribution of final cumulative whole body exposures (mSv) for employees with a radiation record.*

all strata gives the total expected deaths for each exposure group for comparison with the number of deaths observed. To test the ratios for a dose response relation, a one degree of freedom chi-square test for trend, or the corresponding standard normal deviate test, is then performed. From the latter, significance probabilities may be derived on the basis of the test statistic being approximately distributed as a standard normal deviate (SND). All probabilities quoted are based on two sided significance tests.

Given the skewed nature of the distribution of the cumulative exposures (fig 1), it was not obvious how best to group them. The test statistic is not robust when the numbers of deaths are small and could be sensitive to the choice of exposure categories. Simulations of the test statistic were performed for three different groupings of exposure, the lower limits of the exposure categories being:

(*a*) 0, 0·1, 1, 10, and 100 mSv;

(*b*) 0, 5, 10, 20, 40, 80, and 160 mSv, and

(*c*) 0, 10, 20, 50, and 100 mSv.

The first grouping (*a*) was chosen to make the person-years at risk in each exposure category similar and (*b*) and (*c*) to create a greater number of categories at higher exposure levels. The test statistic was simulated separately for totals of 2, 5, 10, 20, 50, and 100 deaths, the simulation for each total being performed 1000 times. Because of the skewed distribution of the exposures, the values chosen for the median exposure in the simulations were the midpoints of each category on a logarithmic scale. On the assumption that the test statistic is normally distributed, the expected values of the mean, variance, skewness, and kurtosis are 0, 1, 0, and 0 respectively. Also 2·5% of the simulated statistics should be less than −1·96 and 2·5% greater than +1·96. The results of the simulation are presented in table 1. It may be seen that although there are no major differences between the three exposure groupings examined, the last (*c*) provides the best approximation to a normal distribu-

Table 1 *Results of 1000 simulations of the trend statistic assuming various numbers of observed deaths and three different groupings of exposure*

No of deaths	*Mean*	*Variance*	*Skewness*	*Kurtosis*	*% < −1·96*	*% > 1·96*
(*a*) *Exposure categories with lower limits of 0, 0·1, 1, 10, and 100 mSv*						
2	−0·04	0·9	2·3	4·2	—	12·8
5	−0·05	0·9	1·4	1·3	—	4·2
10	−0·01	1·0	1·1	1·6	—	2·9
20	−0·02	1·0	0·8	0·8	—	5·4
50	0·02	1·1	0·6	0·3	1·0	3·9
100	−0·01	1·0	0·3	0·2	1·6	3·4
(*b*) *Exposure categories with lower limits of 0, 5, 10, 20, 40, 80, and 160 mSv*						
2	−0·02	0·9	2·1	4·1	—	8·3
5	−0·04	0·9	1·3	1·4	—	4·7
10	0·00	1·0	1·0	1·0	—	4·6
20	−0·01	1·0	0·8	0·9	—	4·5
50	0·02	1·1	0·6	0·9	1·1	3·5
100	0·00	1·1	0·3	0·1	2·4	3·7
(*c*) *Exposure categories with lower limits of 0, 10, 20, 50, and 100 mSv*						
2	−0·01	0·9	1·4	1·5	—	4·8
5	−0·02	0·9	1·0	0·9	—	5·0
10	0·00	0·9	0·8	0·9	—	3·9
20	−0·01	1·0	0·6	0·5	0·5	4·1
50	0·01	1·1	0·5	0·4	1·3	4·2
100	−0·02	1·0	0·2	0·0	2·3	2·7

tion and was chosen for these and previous analyses.[2]

PRECISION OF WHOLE BODY EXPOSURE ESTIMATES

Radiation protection procedures have changed over the years and methods for monitoring exposure have become increasingly sensitive. At the authority's establishment at Harwell, the "threshold" level below which measurements are not made has been only 0·05 mSv* since 1967. From 1961 to 1966 it was 0·15 mSv and in earlier years the threshold level was higher still, being 0·5 mSv from 1948 to 1960 and 1 mSv before 1948. Before 1961 dosimeters were issued on a weekly basis. Thus for each worker receiving 50 dosimeters annually, up to 50 mSv could, in theory, have been obscured within the below threshold readings in each year before 1948 and 25 mSv in each year between 1948 and 1960. From 1961 onwards, dosimeters were generally issued every four weeks, and with the lower threshold level, up to 1·95 mSv could have been obscured annually from 1961 to 1966 but only 0·65 mSv since then.

The exposures contained within these below threshold readings were examined for a sample of old film dosimeters from Harwell. Films dating from 1953 to 1959 were remeasured using modern equipment.[11,12] From these measurements it was possible to derive a formula for estimating each individual's below threshold exposure for the earlier years.[12] The estimate was based on the proportion of each workers' films which were below the threshold level each year. For the years 1948 to 1960 in which the threshold level was 0·5 mSv the following equation was used to estimate an individual's exposure for each below threshold reading (y):

$$y = 0{\cdot}99 - 0{\cdot}93x$$

where x is the proportion of that worker's films which were below the threshold measurement. Although the above equation was derived from Harwell, it is applicable at the other authority establishments except Dounreay. At the Culham Laboratory all dosimeters issued were processed at Harwell; at Winfrith the measurement techniques and rules for distributing dosimeters were similar, until recently, to those practised at Harwell; and the few workers at the London office who have a radiation record all received their exposures elsewhere, mostly at Harwell. At Dounreay, dosimeters were generally issued monthly rather than weekly and the threshold level never exceeded 0·2 mSv. Thus the potential for underestimating exposure at Dounreay is not as great as elsewhere.

Another consideration is that some exposures may remain unknown when dosimeters are not returned, lost, or damaged. The number of weeks during which a dosimeter was issued but the exposure reading was absent was recorded annually for each worker. Each worker's unrecorded exposures resulting from missing dosimeter readings were estimated from that same worker's average weekly measured exposures during the remainder of the year, on the assumption that similar exposure occurred during the weeks when the dosimeter readings were missing.

Figure 2 shows the mean annual whole body exposure of workers at Harwell, Culham, London, and Winfrith from 1946 to 1979 using three different assumptions about below threshold readings and missing values. Assumption A takes these exposures to be zero. This assumption was made in our previous analyses of these data.[2] Assumption B estimates the below threshold exposures for the years up to and including 1960 using the formula y = 0·99 – 0·93x, described above.† After 1960, when the threshold was 0·15 mSv, the below threshold exposures were taken to be zero. The contribution from missing dosimeter readings was estimated from the weekly average of the exposure from existing dosimeters, including the estimated threshold exposure before 1961. Assumption C takes the full value of the threshold level for each below threshold reading, adding the corresponding estimate for missing values.

Figure 2 shows that before 1961 widely differing results are obtained from the three assumptions, there being an almost 10-fold variation in the estimated average exposure depending on whether the below threshold readings are taken to be zero (assumption A) or their maximum values (assumption C). Between 1961 and 1967, assumptions A and C still result in slightly different estimates of average exposures but the difference is less than twofold. After 1967, both assumptions result in similar estimates of average whole body exposures. Taking the below threshold values to be zero has been shown to underestimate exposure in the earlier years.[11,12] The magnitude of the underestimate of the order of 0·1 mSv per film,[11,12] is, however, only one fifth the full threshold value of 0·5 mSv used in the estimations under assumption C. Thus assumption C provides a large overestimate of true exposure and is useful only in indicating an upper limit of the exposure which could be contained in the below threshold readings. The discontinuity of the annual average exposures under assumptions A and C after 1960 (seen in fig 2) is further evidence that neither provides a satisfactory estimate of exposure before 1960. By contrast, the exposures derived under assumption B result in re-estimates of exposure for the earlier years which are

*10 mSv = 1 rem.

†On the occasions where x was less than 0·53 (which occurred for less than 3% of the annual records), y was set to be the threshold value. Before 1948 when the threshold level was 1 mSv the same equation was used and the resulting value of y was doubled.

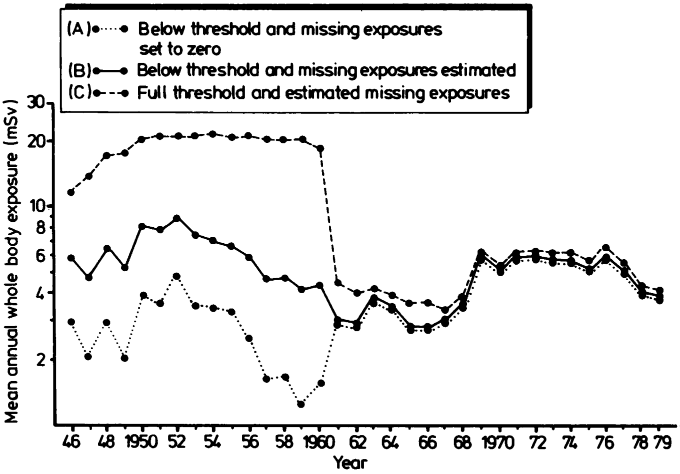

Fig 2 *Mean annual whole body radiation exposures (mSv) using three different assumptions regarding below threshold and missing dosimeter readings (excluding Dounreay employees).*

Table 2 *Mean annual whole body radiation exposures using two assumptions about exposures from below threshold and missing values* (see text for details)*

Year	No of employees monitored	Mean annual whole body exposure (mSv) (A) Below threshold and missing values assumed to be zero	(B) Below threshold and missing values estimated
1946	10	3·00	5·84
1947	206	2·07	4·64
1948	719	2·90	6·24
1949	1221	2·04	5·28
1950	1496	3·96	8·12
1951	1686	3·67	7·73
1952	1849	4·82	8·87
1953	2082	3·54	7·30
1954	2375	3·44	6·91
1955	2752	3·31	6·68
1956	2989	2·50	5·76
1957	3397	1·62	4·65
1958	3893	1·69	4·71
1959	4450	1·26	4·21
1960	4845	1·55	4·33
1961	5070	2·85	2·91
1962	5188	2·80	2·84
1963	5374	3·68	3·74
1964	5414	3·34	3·39
1965	5475	2·74	2·78
1966	5144	2·72	2·77
1967	4760	2·96	3·01
1968	4599	3·52	3·57
1969	4001	5·68	5·79
1970	3897	4·99	5·07
1971	3770	5·68	5·81
1972	3592	5·57	5·66
1973	3456	5·51	5·60
1974	3360	5·50	5·57
1975	3474	5·01	5·07
1976	3459	5·68	5·73
1977	3497	4·78	4·81
1978	3550	3·93	3·95
1979	3591	3·75	3·78

*Excludes information for Dounreay employees.

the most comparable with the later figures. Thus assumption B would seem to provide more reasonable estimates of whole body exposure than do either of the other two assumptions. This conclusion is as might be expected, given that the remeasurement of a sample of old films formed the basis of the estimates in assumption B.[11 12]

RE-ESTIMATING WHOLE BODY EXPOSURE

The exposures reported previously which were based on assumption A[1 2] were re-estimated taking into account below threshold exposures and missing values (assumption B). When this was done the average annual whole body exposures per worker between 1946 and 1960 were about double those obtained if such readings were taken to be zero. Instead of averages of about 2 and 4 mSv a year under assumption A, the average exposure in the years 1946 to 1960 was between 4 and 8 mSv under assumption B (table 2). After 1960 there was little change in the annual average exposures. The effect of the re-estimation was to reduce the number of individuals in the lowest exposure category and to increase the proportion with cumulative exposures of more than 100 mSv (table 3). Because of these changes in the distribution of the study population across exposure categories, the effect on analyses of mortality in relation to exposure was examined.

MORTALITY IN RELATION TO RE-ESTIMATED WHOLE BODY EXPOSURE

The test for trend in mortality with increasing exposure was performed using the re-estimated exposures (assumption B) and contrasted with the findings obtained when assumption A was used. The

Table 3 *Distribution of workers with a radiation record by final cumulative whole body exposure using two assumptions about exposures from below threshold and missing values**

	Final cumulative whole body exposure (mSv)					
Assumption about below threshold and missing values	*< 10*	*10 –*	*20 –*	*50 –*	*≥ 100*	*Total*
(A) Below threshold and missing values assumed to be zero	9948†	1527	1679	914	1055	15 123†
(B) Below threshold and missing values estimated	7972	1994	2501	1339	1317	15 123

*Excludes Dounreay employees.
†One individual included here was excluded from the earlier paper[2] because his sex was unknown at the time of that analysis.

Table 4 *Mortality by cumulative whole body exposure for selected causes of death, 1946–79, using two assumptions about exposures from below threshold and missing values (adjusted for age, sex, social class, calendar period, and authority establishment*)*

		Cumulative whole body exposure (mSv)										Test for trend	
		< 10		*10 –*		*20 –*		*50 –*		*≥ 100*			
Cause of death (ICD code, 8th revision)	*Assumption about below threshold and missing values*	*O/E†*	*(O)*	*O/E*	*(O)*	*O/E*	*(O)*	*O/E*	*(O)*	*O/E*	*(O)*	*SND statistic*	*p Value*
All malignant neoplasms	(A) Both zero	0·97	(282)	0·98	(43)	1·05	(40)	1·20	(22)	1·16	(26)	1·14	0·3
(140–209)	(B) Both estimated	0·95	(171)	0·93	(64)	1·04	(99)	1·06	(41)	1·28	(38)	1·86	0·06
Intestinal cancer	(A) Both zero	1·00	(18)	1·13	(3)	—	(0)	0·99	(1)	2·62	(3)	1·42	0·2
(152–153)	(B) Both estimated	1·05	(12)	0·75	(3)	0·87	(5)	0·87	(2)	1·99	(3)	0·99	0·3
Prostatic cancer	(A) Both zero	0·71	(11)	0·36	(1)	1·21	(3)	1·55	(2)	3·59	(7)	4·23	<0·001
(185)	(B) Both estimated	0·64	(6)	0·55	(2)	0·67	(4)	1·18	(3)	3·80	(9)	4·72	<0·001
All lymphatic and													
haematopoietic	(A) Both zero	0·92	(20)	0·31	(1)	1·57	(4)	1·66	(2)	2·42	(3)	1·93	0·05
neoplasms (200–209)	(B) Both estimated	0·80	(11)	1·33	(7)	0·92	(6)	1·14	(3)	1·62	(3)	1·02	0·3
Non-Hodgkin's	(A) Both zero	0·72	(5)	—	(0)	2·07	(2)	2·22	(1)	4·26	(2)	2·66	0·01
lymphoma (200, 202)	(B) Both estimated	0·45	(2)	1·26	(2)	1·31	(3)	1·01	(1)	3·03	(2)	1·92	0·05
Multiple myeloma	(A) Both zero	0·95	(2)	—	(0)	4·28	(1)	—	(0)	—	(0)	−0·33	0·7
(203)	(B) Both estimated	0·81	(1)	2·00	(1)	—	(0)	4·75	(1)	—	(0)	−0·10	0·9
Leukaemia	(A) Both zero	1·08	(10)	—	(0)	0·86	(1)	1·85	(1)	1·91	(1)	0·72	0·5
(204–207)	(B) Both estimated	1·11	(6)	0·80	(2)	1·03	(3)	0·75	(1)	1·16	(1)	0·00	1·00
All causes	(A) Both zero	0·99	(1030)	1·01	(159)	1·13	(146)	1·07	(66)	0·89	(66)	−0·47	0·6
(000–999)	(B) Both estimated	0·93	(590)	0·98	(250)	1·12	(380)	1·04	(140)	1·07	(107)	1·70	0·09

*Excludes Dounreay employees.
†O/E = Observed deaths divided by expected deaths. (Observed deaths (O) are shown in parentheses.) Expected deaths are calculated using the mortality rates in the total population analysed.

results are presented in table 4 for all causes of death, all cancers, leukaemia, and myeloma and for specific cancer sites that were significantly associated with radiation exposure in this population,[2] where it may be seen that the two assumptions gave rise to somewhat different results. For all cause mortality the relation changed from one in which mortality declined with increasing exposure to one in which mortality increased with increasing exposure. Neither trend reached significance at the 5% level. Mortality from all cancers increased with increasing exposure under both assumptions, but the trend approached statistical significance under assumption B (p = 0·06) and did not under assumption A (p = 0·3). The previously reported highly significant relation between prostatic cancer and exposure also strengthened slightly, with the value of the SND statistic increasing from 4·23 with assumption A to 4·72 with assumption B. Conversely, the trend in mortality from non-Hodgkin's lymphoma with increasing exposure, reported before as being significant at Harwell and adjacent establishments,[2] was weakened under assumption B but nevertheless was significant regardless of the assumption used. It should be noted that the test for all lymphatic and haematopoietic neoplasms was of borderline significance when below threshold and missing values were set to zero (p = 0·05, assumption A). This trend was not statistically significant at any single establishment nor in the previous analysis when data from Dounreay were included.[2] The separate trends for leukaemia and multiple myeloma were not significant under either assumption. Analyses were also performed using the re-estimated exposures with a 15 year lag (table 5). As before, the only condition showing a significant increase in mortality with increasing exposure was prostatic cancer.[2]

As in the previous analysis,[2] excess death rates for all cancers and for leukaemia were calculated for each exposure category as the observed minus the expected

Table 5 *Mortality by cumulative whole body exposure for selected causes of death, 1946–79, lagged by 15 years and estimating below threshold and missing values (adjusted for age, sex, social class, calendar period, and authority establishment*)*

Cause of death (ICD code, 8th revision)	Cumulative whole body exposure (mSv) < 10 O/E†	(O)	10– O/E	(O)	20– O/E	(O)	50– O/E	(O)	≥ 100 O/E	(O)	Test for trend SND statistic	p Value
All malignant neoplasms (140–209)	0·99	(305)	0·99	(39)	1·03	(45)	1·42	(19)	0·57	(5)	0·45	0·7
Intestinal cancer (152–153)	1·04	(20)	1·37	(3)	0·39	(1)	—	(0)	2·98	(1)	0·22	0·8
Lung cancer (162)	1·01	(116)	0·85	(12)	1·17	(18)	1·01	(5)	0·32	(1)	0·95	0·3
Prostatic cancer (185)	0·78	(12)	0·30	(1)	1·25	(4)	4·59	(5)	2·22	(2)	2·93	0·003
All lymphatic and haematopoietic (200–209)	1·09	(25)	0·39	(1)	1·00	(3)	1·16	(1)	—	(0)	−0·77	0·5
Multiple myeloma (203)	1·29	(2)	—	(0)	—	(0)	7·06	(1)	—	(0)	0·24	0·8
Leukaemia (204–207)	1·09	(11)	0·99	(1)	0·80	(1)	—	(0)	—	(0)	−0·93	0·3
All causes (000–999)	0·96	(1033)	1·14	(169)	1·11	(182)	1·25	(59)	0·79	(24)	0·46	0·7

*Excludes Dounreay employees.
†O/E = Observed deaths divided by expected deaths. (Observed deaths (O) are shown in parentheses.) Expected deaths are calculated using the mortality rates in the total population analysed.

Table 6 *Mortality from selected causes of death, 1946–79, for those with a radiation record according to whether or not the worker had missing dosimeter readings for more than 5% of the time during which he/she was monitored (adjusted for age, sex, social class, calendar period, and authority establishment*)*

Cause of death (ICD code, 8th revision)	Missing dosimeter readings < 5% Of monitoring time O/E†	(O)	≥ 5% Of monitoring time O/E	(O)	Test for difference SND statistic	p Value
All malignant neoplasms (140–209)	0·97	(409)	1·16	(78)	1·43	0·2
Lung cancer (162)	0·97	(150)	1·20	(26)	0·89	0·4
Prostatic cancer (185)	1·11	(24)	0·30	(1)	−1·09	0·3
All lymphatic and haematopoietic neoplasms (200–209)	0·96	(34)	1·29	(7)	0·50	0·6
Non-Hodgkin's lymphoma (200, 202)	1·15	(14)	—	(0)	−1·49	0·1
Multiple myeloma (203)	1·13	(4)	—	(0)	−0·06	1·0
Leukaemia (204–207)	0·90	(14)	1·61	(4)	0·72	0·5
All circulatory diseases (390–459)	1·00	(803)	1·02	(131)	0·17	0·9
All respiratory diseases (460–519)	1·01	(131)	0·93	(23)	−0·26	0·8
All accidents (800–999)	0·92	(89)	1·42	(27)	1·98	0·05
All causes (000–999)	0·98	(1550)	1·11	(289)	2·01	0·04

*Includes Dounreay employees.
†O/E = Observed deaths divided by expected deaths. (Observed deaths (O) are shown in parentheses.) Expected deaths are calculated using the mortality rates in the total population analysed.

Table 7 *Distribution of workers with a radiation record by final cumulative neutron, whole body and surface exposures**

Type of exposure	Final cumulative exposure (mSv) < 10	10–	20–	50–	≥ 100	Total
Neutron	19945	273	120	42	3	20 383
Whole body†	10443	2671	3358	1891	2020	20 383
Surface†	9465	2531	3335	2059	2993	20 383

*Includes Dounreay employees.
†Estimated exposures for below threshold and missing values are incorporated here (assumption B in the text). For Dounreay employees the estimated whole body contribution from missing values but not from below threshold readings is included.

deaths, based on national mortality statistics, divided by the person-years at risk. Maximum likelihood methods were used to fit regression lines, the slopes of which were 17·4 (95% confidence interval −21·7 to 62·3) for all cancers, and 0·4 (95% confidence interval −3·2 to 9·9) for leukaemia. These slopes, derived using the re-estimated exposures, are comparable with those obtained previously[2] using the unadjusted exposures for the whole UKAEA study population—that is, 12·5 and 2·2 for all cancers and leukaemia respectively. The slopes of the regression lines provide estimates of the excess deaths per million person-

Table 8 *Mortality from selected causes of death, for those with a radiation record according to whether or not the worker had recorded neutron exposure (adjusted for age, sex, social class, calendar period, and authority establishment*)*

Cause of death (ICD code, 8th revision)	Recorded exposure to neutrons: No O/E†	No (O)	Yes O/E	Yes (O)	Test for difference: SND statistic	p Value
All malignant neoplasms (140–209)	1·02	(417)	0·90	(70)	0·94	0·3
Intestinal cancer (152–153)	0·94	(26)	1·41	(6)	0·67	0·5
Lung cancer (162)	1·01	(147)	0·96	(29)	0·16	0·9
Prostatic cancer (185)	0·84	(17)	1·68	(8)	1·50	0·1
All lymphatic and haematopoietic neoplasms (200–209)	0·97	(34)	1·16	(7)	0·20	0·8
Multiple myeloma (203)	0·87	(3)	1·82	(1)	0·08	0·9
Leukaemia (204–207)	0·97	(15)	1·16	(3)	0·06	1·0
All causes (000–999)	1·02	(1593)	0·89	(246)	2·13	0·03

*Includes Dounreay employees.
†O/E = Observed deaths divided by expected deaths. (Observed deaths (O) are shown in parentheses.) Expected deaths are calculated using the mortality rates in the total population analysed.

years per 10 mSv (1 rem). None of the slopes here differs significantly from zero.

MORTALITY OF WORKERS WITH A HIGH PROPORTION OF MISSING EXPOSURE MEASUREMENTS

In the preceding analyses radiation exposure was estimated when dosimeter readings were missing assuming that each individual's existing exposure measurements were representative of the missing ones. This assumption may not be valid and if not such estimates might be especially poor in workers with many missing values. The question then arises as to whether the mortality pattern of such employees differs from that in the remainder of the workforce. A group of 3512 workers (17% of those with a radiation record) had missing readings for more than 5% of the time during which they were monitored. A comparison of their mortality with that of the remaining 16871 employees with a radiation record is shown in table 6. All cause mortality was significantly higher ($p < 0·05$) among the employees whose readings were missing for more than 5% of the time. Some contribution to this excess came from deaths attributed to accidents and violence, causes of death which were also significantly increased in those with missing dosimeters ($p = 0·05$). Mortality from all cancers was also slightly higher for this group but the excess was not significant and, in general, mortality from most specific causes differed little from that of other workers.

Table 9 *Mortality by cumulative surface exposure for selected causes of death, 1946–79, (adjusted for age, sex, social class, calendar period, and authority establishment*)*

Cause of death (ICD code, 8th revision)	Cumulative surface exposure (mSv): <10 O/E†	<10 (O)	10– O/E	10– (O)	20– O/E	20– (O)	50– O/E	50– (O)	≥100 O/E	≥100 (O)	Test for trend: SND statistic	p Value
All malignant neoplasms (140–209)	0·92	(175)	0·89	(65)	1·05	(109)	1·09	(57)	1·20	(81)	2·30	0·02
Intestinal cancer (152–153)	1·06	(13)	0·43	(2)	1·02	(7)	1·21	(4)	1·22	(6)	0·66	0·5
Lung cancer (162)	0·95	(64)	0·81	(22)	0·97	(37)	1·29	(24)	1·18	(29)	1·44	0·1
Breast cancer (174)	1·16	(3)	1·19	(1)	—	(0)	—	(0)	—	(0)	−0·75	0·5
Prostatic cancer (185)	0·67	(6)	0·57	(2)	0·51	(3)	1·03	(3)	2·88	(11)	4·16	<0·001
All lymphatic and haematopoietic neoplasms (200–209)	0·80	(13)	1·56	(9)	0·81	(7)	0·44	(2)	1·72	(10)	1·64	0·1
Non-Hodgkin's lymphoma (200, 202)	0·74	(4)	1·52	(3)	0·36	(1)	1·21	(2)	1·79	(4)	1·40	0·2
Multiple myeloma (203)	0·66	(1)	2·00	(1)	—	(0)	—	(0)	3·63	(2)	1·82	0·07
Leukaemia (204–207)	0·91	(6)	1·19	(3)	1·46	(6)	—	(0)	1·16	(3)	0·00	1·00
All causes (000–999)	0·94	(667)	0·99	(280)	1·10	(429)	1·06	(209)	0·98	(254)	0·37	0·8

*Includes Dounreay employees.
†O/E = Observed deaths divided by expected deaths. (Observed deaths (O) are shown in parentheses.) Expected deaths are calculated using the mortality rates in the total population analysed.

NEUTRON EXPOSURE

Information on the neutron component of each individual's annual whole body exposure was collected for this study. The distribution of employees, including those at Dounreay, by final cumulative neutron exposure is presented in table 7. Although recorded exposure from neutrons is low in the authority's workforce, the 4179 individuals with any recorded neutron exposure had comparatively high exposures from other forms of radiation—45% had cumulative exposures from X and γ rays exceeding 50 mSv compared with only 12% for workers without any recorded neutron exposure. Those with recorded neutron exposure had significantly lower mortality overall ($p = 0.03$) than other workers with a radiation record (table 8). Cancer mortality in this group was also lower than in other workers but not significantly so, and for no specific cancer site was there a significant difference between the two groups. The numbers were insufficient to test for a trend with increasing exposure.

SURFACE EXPOSURE

Surface exposure is the sum of whole body exposure plus exposures from β particles and low energy photons. The recorded surface exposures are therefore greater than the whole body readings (table 7) but are highly correlated with them. Analyses of mortality by surface exposure are presented in table 9 and include Dounreay employees, whose estimates of exposure were adjusted for missing readings. The trend in mortality was significantly for all cancers ($p = 0.02$), highly significant for prostatic cancer ($p < 0.001$), and of borderline significance for multiple myeloma ($p = 0.07$). Mortality from all cancers increased with increasing surface exposure at each establishment but the trend did not reach statistical significance at any one of them alone. There were only four deaths from multiple myeloma and since the test statistic may be unstable with small numbers, the significance probability was calculated by simulation. This yielded a value of 0·07, the same as that obtained using the standard method.

Cancer incidence

THE DATA

Since 1971, arrangements have been made for cancers registered by regional registries to be notified to the National Health Service Central Registers.[13] The central ethical committee of the British Medical Association granted the Epidemiological Monitoring Unit permission to receive depersonalised cancer registration data for the study population. This information was collected for ex-employees only because the prime purpose of the study was to examine the mortality of the workforce, and the Office of Population Censuses and Surveys was reluctant to flag and place under continuous surveillance workers still employed by the authority, and known to be alive, at the end of the study period (31 December 1979). A total of 656 registrations was notified to the Epidemiological Monitoring Unit for the period 1971–9 for those last employed at sites other than Dounreay: 490 in those last employed at Harwell; 27 at Culham; 51 at the London office; and 88 at Winfrith. Cancer registration data for Dounreay ex-employees were not available in time to be included in this analysis.

Some subjects, employed by the authority when their cancers were registered, died subsequently, and information about their registrations was sent to the Epidemiological Monitoring Unit retrospectively after termination of employment. Of 45 such subjects who had a radiation record, 82% were still employed by the authority at the time of death, compared with only 61% of 41 employees without a radiation record. This suggests that radiation workers may be less likely than others to leave the authority once they

Table 10 *Registrations of selected non-fatal cancers in ex-employees with and without a radiation record, 1971–9 (adjusted for age, sex, social class, calendar period, and authority establishment*)*

Cancer site (ICD code, 8th revision)	*Without a radiation record*		*With a radiation record*		*Test for difference*	
	O/E†	*(O)*	*O/E*	*(O)*	*SND statistic*	*p Value*
All malignant neoplasms (140–209)	0·95	(123)	1·07	(108)	0·94	0·3
Intestinal cancer (152–153)	0·87	(8)	1·12	(11)	0·34	0·7
Skin cancer (172–173)	0·89	(26)	1·12	(32)	0·82	0·4
Breast cancer (174)	0·82	(25)	1·90	(12)	2·45	0·01
Prostatic cancer (185)	0·98	(6)	1·01	(10)	0·20	0·8
Testicular cancer (186)	1·39	(4)	0·73	(3)	0·54	0·6
Bladder cancer (188)	1·04	(14)	0·97	(14)	0·00	1·00
All lymphatic and haematopoietic neoplasms (200–209)	1·17	(10)	0·78	(5)	0·56	0·6
Leukaemia (204–207)	1·16	(4)	0·79	(2)	0·03	1·0

*Excludes Dounreay employees.
†O/E = Observed registrations divided by expected registrations. (Observed registrations (O) are shown in parentheses.) Expected registrations are calculated using the registration rates in the total population analysed.

Table 11 *Registrations of selected non-fatal cancers in ex-employees with a radiation record by cumulative whole body radiation exposure, 1971–9 (adjusted for age, sex, social class, calendar period, and authority establishment*). Missing and below threshold exposures estimated (assumption B)*

Cancer site (ICD code, 8th revision)	*Cumulative whole body exposure (mSv)* < 10 O/E†	(O)	10– O/E	(O)	20– O/E	(O)	50– O/E	(O)	≥ 100 O/E	(O)	*Test for trend* SND statistic	p Value
All malignant neoplasms (140–209)	0·92	(51)	1·13	(19)	0·99	(21)	1·17	(10)	1·15	(7)‡	0·67	0·5
Intestinal cancer (152–153)	0·79	(4)	1·67	(3)	1·79	(4)	—	(0)	—	(0)	−1·01	0·3
Skin cancer (172–173)	0·96	(14)	0·98	(5)	0·53	(4)	1·58	(5)	2·40	(4)	1·91	0·06
Breast cancer (174)	0·82	(7)	1·14	(2)	1·55	(2)	4·18	(1)	—	(0)	0·46	0·6
Prostatic cancer (185)	0·67	(3)	1·48	(3)	0·88	(2)	1·51	(1)	1·68	(1)	0·75	0·5
Testicular cancer (186)	0·60	(1)	—	(0)	—	(0)	14·06	(2)	—	(0)	1·34	0·2
Bladder cancer (188)	0·91	(6)	—	(0)	1·80	(5)	—	(0)	3·31	(3)	1·89	0·06
All lymphatic and haematopoietic neoplasms (200–209)	1·21	(3)	1·48	(1)	1·14	(1)	—	(0)	—	(0)	−0·98	0·3
Leukaemia (204–207)	2·45	(2)	—	(0)	—	(0)	—	(0)	—	(0)	−0·97	0·3

*Excludes Dounreay employees.
†O/E = Observed registrations divided by expected registrations. (Observed registrations (O) are shown in parentheses.) Expected registrations are calculated using the registration rates in the total population analysed.
‡The difference between this total and the sum for the specific cancer sites is explained by multiple cancer in the same individual.

have a cancer diagnosed. Thus unbiased analyses of cancer incidence were possible only for cancers first registered after leaving the authority's service. Furthermore, fatal cancers dominate the cancer registrations for most sites and, as analyses of fatal cancers have been reported previously,[2] the data analysed here were restricted to registered cancers which had not resulted in death by the end of 1979.

FINDINGS

Table 10 shows the results of analyses relating non-fatal registered cancers to the presence or absence of a radiation record. There was a significant excess ($p < 0.05$) of registrations of non-fatal female breast cancer among those with a radiation record. Analyses of non-fatal cancers in relation to re-estimated cumulative whole body exposures (table 11) showed no clearly significant dose response relations at the 5% level, although the trends for skin cancer and bladder cancer approached statistical significance ($p = 0.06$ for both cancers).

Discussion

Employees of the UKAEA who may be exposed to ionising radiation are required to wear personal dosimeters to provide a measure of the extent of their exposure. Records of the dosimeter readings are kept but in some cases no numerical value is available, as a dosimeter may be lost or damaged or the associated exposure may be below the level of detection of the measuring devices used. Over the years, the methods of reading radiation film dosimeters have become increasingly sensitive. Before 1948, the threshold below which measurements were not made was 1 mSv. Now the threshold level is 20 times lower at 0·05 mSv. Using modern techniques, the remeasurement of whole body exposures at Harwell showed that before the 1960s an average of 0·1 mSv per film badge had been classified as "below threshold."[11 12] Although the value of 0·1 mSv per film is low, the average measured whole body exposures at the time were low as well so that the unmeasured below threshold component constitutes an important fraction of total exposure. Average exposures of the order of 2 to 4 mSv a year were recorded before 1961, and these would have approximately doubled had the contribution from the below threshold exposures been included (table 2). Thus, as others have pointed out,[14] below threshold exposures can be important in circumstances where the average measured exposures are low and where dosimeters are issued frequently. The extent to which this has resulted in underestimates of exposure here has varied over time, it being most important before 1961 when measuring techniques were least sensitive and the dosimeters were issued most frequently.

When exposures were re-estimated, allowing for below threshold and missing readings, some of the findings relating mortality to whole body exposure altered. The changes were mostly minor but it is noteworthy that for all cancers the linear trend approached significance ($p = 0.06$) with the re-estimated exposures, but was far from significant without the re-estimations ($p = 0.3$). These changes, although of interest, did not substantially alter the risk estimates, or the conclusions, in the previous report.[2] Workers who had a large proportion of their dosimeter readings missing had higher mortality, especially from accidents and other violence, as compared with the radiation workers with more complete radiation histories.

Further considerations relate to forms of radiation exposure not usually measured as whole body exposure. Workers with any recorded exposure from neutrons had significantly lower mortality than the remaining workers with a radiation record ($p = 0 \cdot 03$). The finding is not consistent with other observations in this workforce in that cancer mortality was found to increase with whole body exposure and those with neutron exposures tended on average to have high whole body exposures. Their low mortality may be a chance finding or there may be special forces operating in the selection of workers for jobs involving possible exposure to neutrons. Surface exposure was significantly associated with mortality from prostatic cancer ($p < 0 \cdot 001$) and from all cancers ($p = 0 \cdot 02$). Surface and whole body exposure are correlated and the trend for prostatic cancer is consistent with other findings in this workforce. It is not clear why the association for all cancers appears to be stronger for surface than for whole body exposure. If not due to chance it could be that surface exposure is correlated with exposure to other radionuclides or chemicals. The trend in multiple myeloma mortality, which increased with increasing surface exposure, approached significance ($p = 0 \cdot 07$) and is of interest as this malignancy was related to radiation exposure in the studies of workers at the Hanford and at the Sellafield plants.[7-9 15] It should be pointed out that in all analyses sources of exposure such as natural background radiation—of the order of 1 mSv per person a year—and exposures associated with medical diagnostic and therapeutic procedures could not be taken into account. They were assumed to be independent of radiation exposure in the workplace.

An attempt to analyse cancer incidence by radiation exposure was hampered by the limitations of the data. Since workers still employed by the authority on 1 January 1980 had not been flagged in the National Health Service Central Registers, analyses were necessarily restricted to a group of ex-employees who may not have been representative of the workforce as a whole. Thus the finding of a significantly higher rate of non-fatal breast cancer in women with a radiation record cannot be readily interpreted, especially since it was not supported by the data for fatal breast cancer, where higher mortality was observed in those without a radiation record.[2] Cancer registration data can only provide a valid supplement to analyses based on mortality if the cancers in current employees as well as ex-employees are included.

In conclusion, the data presented here illustrate some of the problems encountered in relating the mortality of a workforce to different levels of occupational radiation exposure when the exposures themselves are low, cannot be measured accurately, and have been assessed in different ways over time. Dosimeter readings are imperfect surrogate measures of the doses received by the internal organs, because the relation between the dose impinging on a dosimeter and the dose absorbed by the tissues is not straightforward. Moreover some dosimeter readings may be missing or be below the threshold level of the measuring devices in use. When exposure levels can be substantially altered by different assumptions about the magnitude of the below threshold doses and of the missing values, the results of analyses of mortality in relation to exposure must be examined carefully. In those circumstances it is necessary to consider the extent to which the conclusions might be affected by different assumptions. Whereas the re-estimation of whole body exposure in the population resulted in some changes in the findings in this study none was of sufficient magnitude to alter the conclusions reported earlier.[2] Finally, some of the observations on mortality in relation to surface, neutron, and radionuclide exposure suggest that measures other than whole body exposure should be considered in studies of occupational exposure to low dose ionising radiation.

Members of the Epidemiological Monitoring Unit were funded by the Medical Research Council, which held a contract with the UKAEA to perform the study. It was possible only because of the cooperation and advice of many people from different organisations, including the Medical Research Council, UKAEA, Office of Population Censuses and Surveys, General Register Office for Scotland, National Health Service Central Registers, Department of Health and Social Security, Oxford Cancer Registry, and World Health Organisation. We thank all who helped us, especially the members of the Medical Research Council subcommittee and its chairman, Dr R Mole; the UKAEA staff, who are too numerous to name individually; and Lucy Carpenter, Geoffrey Rose, Peter Smith, Martin Shipley, Helen Edwards, and Tina Organ.

References

1 Fraser P, Booth M, Beral V, Inskip H, Firsht S, Speak S. Collection and validation of data in the United Kingdom Atomic Energy Authority mortality study. *Br Med J* 1985;**291**:435–9.
2 Beral V, Inskip H, Fraser P, Booth M, Coleman D, Rose G. Mortality of employees of the United Kingdom Atomic Energy Authority, 1946–79. *Br Med J* 1985;**291**:440–7.
3 International Commission for Radiological Protection. *Limits for intakes of radionuclides by workers*. Oxford: Pergamon Press, 1978. (Publ 30 and supplements.)

4 World Health Organisation. *International classification of diseases*. 8th rev. Geneva: World Health Organisation, 1965.
5 Cox DR. Regression models and life-tables. *Journal of the Royal Statistical Society B* 1972;**34**:187–220.
6 Gilbert ES. The assessment of risks from occupational exposure to ionizing radiation. In: Breslow NE, Whittemore A, eds. *Energy and health*. Philadelphia: Society for Industrial and Applied Mathematics, 1979:209–25.
7 Kneale GW, Mancuso TF, Stewart AM. Hanford radiation study III: a cohort study of the cancer risks from radiation to workers at Hanford (1944–77 deaths) by the method of regression models in life-tables. *Br J Ind Med* 1981;**38**:156–66.
8 Gilbert ES, Marks S. An analysis of the mortality of workers in a nuclear facility. *Radiat Res* 1979;**79**:122–48.
9 Darby SC, Reissland JA. Low levels of ionising radiation and cancer—are we underestimating the risk? *Journal of the Royal Statistical Society A* 1981;**144**:298–331.
10 Gilbert ES. An evaluation of several methods for assessing the effects of occupational exposure to radiation. *Biometrics* 1983;**39**:161–71.
11 Smith JW, McGuinness EA. *Remeasurement of early Harwell personnel film dosimeters*. London: HMSO, 1981. (AERE-R9415.)
12 Smith JW, Inskip H. Estimation of below measurement threshold doses following the remeasurement of a sample of old films. *Journal of the Society for Radiological Protection* 1985;**5**(4): 159–64.
13 Office of Population Censuses and Surveys. *The National Health Service central register as an aid to medical research. A guide for potential applicants*. London: OPCS.
14 Darby SC, Kendall GM, Greenslade E. Patterns of dose incurred by workers on the National Radiological Protection Board's dose record keeping service. II. Individual dosimeter assessments. *Journal of the Society for Radiological Protection* 1982;**2**(4):31–8.
15 Smith PG, Douglas A. Mortality of workers at the Sellafield plant of British Nuclear Fuels. *Br Med J* 1986;**293**:845–54.

Correspondence and editorials

The *British Journal of Industrial Medicine* welcomes correspondence relating to any of the material appearing in the journal. Results from preliminary or small scale studies may also be published in the correspondence column if this seems appropriate. Letters should be not more than 500 words in length and contain a minimum of references. Tables and figures should be kept to an absolute minimum. Letters are accepted on the understanding that they may be subject to editorial revision and shortening.

The journal now also publishes editorials which are normally specially commissioned. The Editor welcomes suggestions regarding suitable topics; those wishing to submit an editorial, however, should do so only after discussion with the Editor.